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Kinetic simulation of a source dominated plasma–wall interaction in an oblique magnetic field

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Abstract

The strongly inhomogeneous region of plasma–wall interaction in the presence of an oblique magnetic field, exhibits many complexities in its kinetic behavior. The normal flows develop due to the presence of strong $E \times B$ drift and its shear. Other kinetic features present in such systems include open orbits, orbits trapped against the wall and orbits that are strongly deformed due to the strong electric fields present near the sheath edge. Such effects need to be modeled kinetically for the exact boundary conditions at the entrance of plasma boundary layer [J. Phys. D 24 (1991) 493]. In the present work, an extensive kinetic simulation of region of magnetized plasma–wall interaction, sustained self-consistently by a Maxwellian source is done. The singular behavior of kinetic equation in the small parallel electric-field region [Comm. Plasma Phys. Control. Fus. 16 (1995) 255] is handled by incorporating a weak collisionality in the ions. A spatially resolved three-dimensional ion velocity distribution function is calculated on a regularly spaced velocity space grid, utilizing the time reversibility of characteristics of the Boltzmann equation inside the region of interaction. It is observed that the normal flow indeed develops from a parallel flow because of the shear in $E \times B$ flow in case of an oblique incidence.

Keywords: Simulation; Plasma wall interaction

1. Introduction

The mechanisms involved in the development of intense cross-field flows into the plasma boundary layer at the plasma–wall interface is a subject of active investigation. The intensity of these cross-field flows determines the exact boundary conditions for the parallel plasma flow leaving the region of magnetized presheath as well as the plasma flux into the Debye sheath in front of the solid surface [3]. In the region of last mean free path the dynamics of ions is mostly governed by the ion inertia but if an intense source is present, the dynamics of ion flows depend largely on the source strength. In a source driven presheath therefore the plasma flows reach the sonic velocities in a region whose scale-length is determined by strength of the source, rather than by collisional effects. The presence of a source injecting a particular velocity distribution of particles introduces many complexities in the kinetic behavior of the system. The particles originating in the bulk simply fall down the presheath potential. However, source particles, generated close to the wall have to climb the presheath potential. They may be reflected back and contribute to the local density or they may be energetic enough to enter the bulk. The exact descriptions of a source dominated magnetized presheath therefore requires a kinetic approach [1].

In the present paper, we focus mainly on the mechanism by which a strong cross-field flow develops along the direction normal to the solid surface in the quasi-neutral region of an oblique magnetized presheath in order to meet the hydrodynamic Bohm criterion. The existing theoretical investigations of magnetized presheath conclude that an acceleration of plasma in the $E \times B$ direction plays a decisive role in the development of the cross-field flows inside a magnetized presheath [4]. In the same context the simulation results presented in

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this paper show that the perpendicular flow is generated only in the presence of a finite derivative of the presheath electric field, which is a situation where an effective acceleration along $E \times B$ can exist.

Since a presheath profile cannot be self-consistently determined in absence of a spatially varying electric field, the particle distribution function is simulated in an artificial stepwise constant electric-field profile and it is observed that the value of the perpendicular flow is constant in presence of a constant field. However self-consistent profiles could be simulated for a source driven magnetized presheath, when the electric field is allowed to have non-zero gradients and the development of perpendicular flows is observed.

As both source and collisions generally scale over the length scales much larger than the Debye length λ_D, we investigate only the quasineutral region of magnetized presheath which scales with the ion Larmor radius ρ_i. Flows are driven combinely by sources and weak collisions into the region of Debye sheath formed in front of the absorbing wall. The paper is organized as follows: Section 2 presents the model equations, Section 3 presents the numerical procedure, and Section 4 presents and discusses the results obtained.

2. The formulation

The geometry of the simulation region is presented in Fig. 1. A plasma is assumed in contact with a fully absorbing wall located at $x = x_{\text{wall}}$. The x-axis is therefore normal to the wall. A magnetic field $\mathbf{B} = B_x\hat{\mathbf{x}} + B_z\hat{\mathbf{z}}$ is assumed to be incident on the wall at an angle θ. All spatial derivatives are assumed along x with y and z ignorable.

Collisions are modeled by a particle conserving Krook type collision operator. Thus, the ion distribution function $f(x, \mathbf{v})$ evolves according to the equation

$$\frac{\partial f}{\partial t} + v_x \frac{\partial f}{\partial x} + \mathbf{a} \cdot \frac{\partial f}{\partial \mathbf{v}} = -\nu\{f - n(x)g(\mathbf{v})\} + s(x, \mathbf{v}), \qquad (1)$$

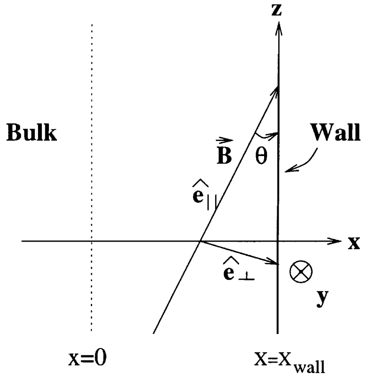

Fig. 1. The geometry of the region, magnetic field **B** is in the x–z plane, making an angle θ with the solid surface.

where $\mathbf{v}$ is the particle velocity, $\mathbf{a}$ the particle acceleration due to the electric and magnetic fields, $s(x, \mathbf{v})$ the source of plasma particles, ν the ion-neutral collision frequency (assumed velocity independent) and $g(\mathbf{v}) = f_m$ a Maxwellian distribution normalized to unit density with the temperature T_0 equal to the electron temperature T_e which is assumed constant and $n(x)$ is the local fluid density defined by

$$n(x) = \int f \, d^3v. \qquad (2)$$

The electrons are confined by the presheath and sheath potential and are in equilibrium with the bulk plasma. The plasma density is therefore approximated by the Boltzmann relation

$$n(x) = n_e(x) = n_0 \exp\left(-\frac{q_e(\phi - \phi_0)}{T_e}\right), \qquad (3)$$

where $n(x)$ and $\phi(x)$ are the density and potential, respectively, and the subscript 0 indicates their values at the bulk.

Eq. (1) is a first order, linear, partial differential equation and may be solved along the characteristics. These characteristics $\xi = (\mathbf{x}, \mathbf{v})$, are the single particle orbits of ions in the applied magnetic field $\mathbf{B}$ and the presheath electric field $\mathbf{E} = E\hat{\mathbf{x}}$ given by the solutions of ion equation of motion:

$$m_i \frac{d\mathbf{v}}{dt} = q_i\mathbf{E} + \frac{q_i}{c}(\mathbf{v} \times \mathbf{B}). \qquad (4)$$

Along a characteristics, Eq. (1) acquires the form of a linear, first order, ordinary differential equation

$$\frac{df(\tau; \xi_0)}{d\tau} = -\nu[f(\tau; \xi_0) - n(\tau; \xi_0)g(\tau; \xi_0)] + s_0(x(\tau; \xi_0))g(\tau; \xi_0), \qquad (5)$$

where, τ is the 'Lagrangian time', $\xi_0 = (\mathbf{x}_0, \mathbf{v}_0)$ the initial phase space coordinates of the orbit, and the source has been assumed to be a spatially inhomogeneous Maxwellian source having the form

$$s(x, \mathbf{v}) = s_0(x)g(\mathbf{v}). \qquad (6)$$

Here, $s_0(x)$ determines the spatial variation of the source strength. Solving for f requires the knowledge of the value of f at some point along the orbit. This point corresponds to the location in past time of the orbit where it intersected the boundaries of the system.

Given the orbit, Eq. (5) is a linear ordinary differential equation, and is easily solved for $f(\tau; \xi_0)$. The solution is linear (but non-local) function of $s_0(\tau; \xi_0)$. The density at any location x is given by a velocity integral over $f(\tau; \xi_0) = f(x, \mathbf{v})$ done at x, which yields symbolically

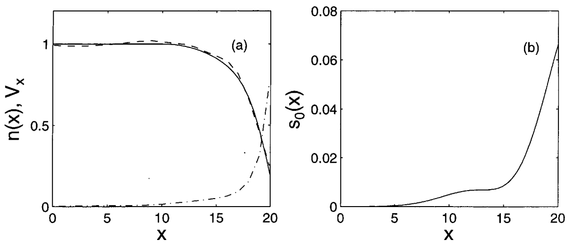

Fig. 2. (a) The density $n(x)$ vs. x at $\theta = 10°$. The solid curve corresponds to the input profile while the broken line represents the output profile after the convergence. Another dotted broken line shows the drift V_x. (b) The source profile determined from the self-consistent run with a presheath-like field profile for $\theta = 10°$.

$$n(x) = \int \Lambda_0(x, \mathbf{v})\, d^3v + \int\int s_0(x')\Lambda_1(x, x', \mathbf{v})\, d^3v\, dx', \quad (7)$$

where, Λ_0 is the contribution to f from the boundaries and Λ_1 is the contribution from the source. However, the part of Λ_0 that come from the wall is zero as the wall is fully absorbing. Since Λ_0 and Λ_1 themselves depend on $n(x)$, Eq. (7) is a non-linear, integro-differential equation for the density profile which is in general difficult to solve self-consistently even by numerical means.

An alternate view of Eq. (7) is to regard it as a problem to determine the source profile, $s(x, \mathbf{v})$ for given $n(x)$. The problem then reduces to the solution of a linear, integro-differential equation. These solutions are worked out for physically valid presheath electric-field profiles and the corresponding $n(x)$, V_x and source profiles are presented in Fig. 2. The resulting source profile have a physically acceptable form, i.e., positive everywhere and varying monotonically from bulk to wall. Here we do a comparison of these self-consistent presheath solutions with the solutions generated in an stepwise constant electric-field profile.

3. Simulation scheme

A set of characteristics, if launched using regularly spaced values of the initial condition from the boundary (where the value of f is known) becomes non-uniformly spaced in the interior, due to the complex nature of the particle orbits. The distribution function is therefore not obtained on a regular mesh in the ion velocity space at interior points in the region of interaction. Since this is highly desirable to have f on a regular velocity mesh, a novel simulation scheme is used. For each location x_i where the distribution is required, a regular mesh (x_i, v_{jkl}) is constructed in velocity space. The orbits passing through each phase space point (x_i, v_{jkl}) are then calculated by solving Eq. (4) 'backwards' in time. The phase space locations where orbits intersect the boundaries are thus determined. The kinetic equation (5) is then solved along the same orbits, starting from the boundary and integrating forward in time using Eq. (4) to obtain the value of f at (x_i, v_{jkl}). Velocity space moments are now taken of these distribution functions at each position x_i to yield kinetic equivalent of the fluid profiles.

The size of simulation region in the simulations is fixed to be $20\rho_i$ normal to the wall. In all the runs, the mean free path, λ_{mfp} (calculated with T_e), is chosen to be $10\rho_i/\sin\theta$ so that the system size is always $2\lambda_{mfp}$. This choice ensures the value of collision frequency ν such that a thermal ion traveling along the magnetic field would meet with a single collision while traversing the presheath region. The source profile is localized to lie within a λ_{mfp} from the wall. Thus, the presheath region could be identified as the right half of the simulation region. The other half is a connection region joining the presheath to the bulk which is a field-free region as can be seen from Fig. 2. Although a residual drift can be seen in this region due to the part of the distribution function which is associated with the characteristics that originated from the wall and which thermalizes only after at least one mean free path in this field-free region. A corresponding residual source can also be seen that becomes vanishingly small towards $x = 0$.

This presence of weak collisions is essential in a source driven simulation, since only collisions are able to keep the distribution function regular at $v_\parallel = 0$ in the region where the electric field is very small or zero [2]. In more physical terms, in the zero-field region the $v_\parallel \simeq 0$ ions stay in the region for many gyroperiods and build up a large value for $f(v_\parallel \simeq 0)$ which is physically incorrect even within the last mean free path.

To determine the distribution function f in a given presheath electric field self-consistently, we use $f(x = 0, v_x > 0) = f_m$ and $f(x_w, v_x < 0) = 0$, at the boundaries. The final electric field and source profiles are determined such that the following conditions are satisfied in addition:

(a) $f(x_0, v_x < 0) = f_m$, i.e., the returning f is also a stationary Maxwellian at $x = 0$, so that a zero flux is ensured across $x = 0$.

(b) The input and output electric-field profiles agree with each other.

A physical, monotonically increasing density profile, for with the f is determined, is drawn from a hydrodynamic model. The output density, V_x and source profiles are presented in Fig. 2.

To study the kinetic response to a presheath-like electric field, the same source profile and boundary conditions are used. However, we do not impose conditions (a) and (b) on the output and use an electric field given as follows:

$$E = \begin{cases} 0 & \text{for } x < 10\rho_i, \\ (T_e/e)/(10\rho_i) & \text{for } x > 10\rho_i, \end{cases} \quad (8)$$

that is, the field is abruptly raised to a constant value on entry into the designated presheath region. The value of the field in the presheath is chosen to make the wall potential approximately equal in both cases. The Electric field and density therefore are no longer coupled through the Boltzmann relation but through an unknown model, that would yield the output density profile for a stepwise constant electric field. By this means, it becomes possible to compare the perpendicular flows that result in a self-consistent system and in a nearly equivalent system without shear.

4. Results and discussion

The components of the velocity vectors were derived by finding the moments of distribution function numerically. The only cross-field velocity component which contributes to the normal velocity is $V_\perp$ since V_y is parallel to the solid surface. Figs. 3–5 present (a) the self-consistent profile and (b) the profile obtained in response to the step profile given in Eq. (8). Fig. 3 is for the case of $\theta = 60°$, while Figs. 4 and 5 are for the case of $\theta = 30°$ and $\theta = 10°$, respectively. The self-consistent cases all show sizable cross-field flows towards the wall. However, the cases that used a step electric field shows almost no cross-field flows towards the wall. This effect is modeled analytically with an assumed $E \times B$ flow shear in [5]. The residual drift that is present in the latter cases may be explained by the slowing down effect due to the source along the $E \times B$ direction. The injection of a distribution with zero cross-field drift causes the existing momentum along y to be shared by more particles. Thus, there is a deceleration in particle velocity, which is an effective force along y. This force causes a weak drift in $V_\perp$.

Close to the wall the scraping off of the particles by the absorbing wall as well as a frictional force along y cause an effect that appears in the figures as a rise in $V_\perp$ very close to the wall. For the 60° case a bump is also seen at $x = 10$, the location where the electric field abruptly jumps from zero to its presheath value. This

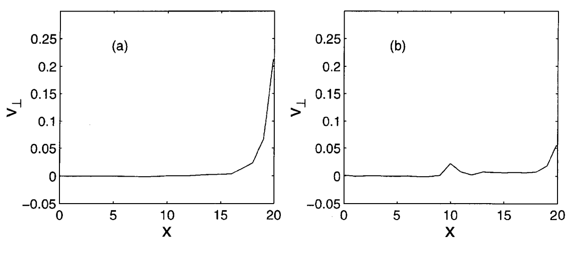

Fig. 3. The cross-field velocity $V_\perp$ vs. x at $\theta = 60°$ for: (a) a presheath-like electric field; (b) a stepwise constant electric field.

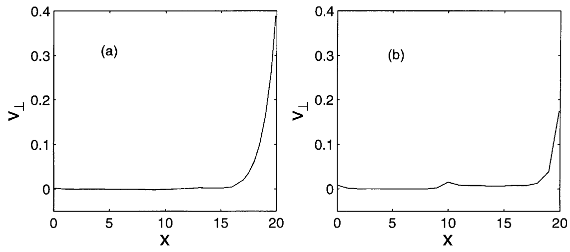

Fig. 4. The cross-field velocity $V_\perp$ vs. x at $\theta = 30°$ for: (a) a presheath-like electric field; (b) a stepwise constant electric field.

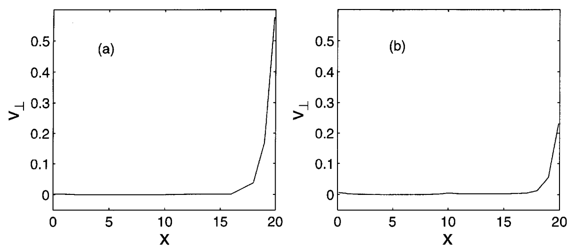

Fig. 5. The cross-field velocity $V_\perp$ vs. x at $\theta = 10°$ for: (a) a presheath-like electric field; (b) a stepwise constant electric field.

bump is expected in all three cases, due to the presence of very localized shear. However, for having an effect, particle that experiences the sudden electric field should not come back, thereby experiencing the same shear in reverse. The fraction of the particles that pass through this high shear region only once is proportional to V_x. For large θ, V_x is dominated by $V_\parallel$ and hence the relatively large bump in the $V_\perp$ profile. For smaller θ, V_x is less, and so is the size of the bump.

All the step-field cases show negligible drift in the presheath region. This confirms the notion that for open orbits to develop, it is the finite variation in the electric field that is important [6]. Both the presheath-like and the stepwise constant field runs used the same source profiles and had the same wall potentials. Yet, only in the presheath-like cases, where the shear in the $E \times B$ flow increases monotonically towards the wall, does the perpendicular drift show the expected increase close to the wall, characteristics of open orbits.

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